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Binaural Processing of Multiple Sound Sources

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The AFOSR Grant, FA9550-12-1-0312, has supported the Spatial Hearing Laboratory (SHL) at Arizona State University for the past four years. The research conducted in the SHL has involved four main topics: Sound Source Localization by Cochlear Implant (CI) Patients, Single Sound Source Localization Accuracy, Multiple Sound Source Localization Identification, and Sound Source Localization When Listeners Move. The CI research was also supported by an NIH grant ('Cochlear Implant Performance in Realistic Listening Environments,' Dr. Michael Dorman, Principal Investigator, Dr. William Yost unpaid advisor. The other three topics cited above are entirely within the scope of the AFOSR grant.

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Binaural Processing of Multiple Sound Sources

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The AFOSR Grant, FA9550-12-1-0312, has supported the Spatial Hearing Laboratory (SHL) at Arizona State University for the past four years. The research conducted in the SHL has involved four main topics: Sound Source Localization by Cochlear Implant (CI) Patients, Single Sound Source Localization Accuracy, Multiple Sound Source Localization Identification, and Sound Source Localization When Listeners Move. The CI research was also supported by an NIH grant ("Cochlear Implant Performance in Realistic Listening Environments," Dr. Michael Dorman, Principal Investigator, Dr. William Yost unpaid advisor). The SHL was also used in 2014 to support a small short-term research project funded by a contract from the Boeing Corporation awarded to Dr. Yost. This project involved collecting data for Boeing Corporation (there were no publications or presentations of these data) on the sound source localization of very low frequency (<60 Hz) sounds. The other three topics cited above are entirely within the scope of the AFOSR grant.

Sound Source Localization by Cochlear Implant Patients

Many experiments have been conducted using a methodology developed by Dr. Yost to efficiently measure sound source localization accuracy in the front azimuth plane at pinna height. Baseline sound source localization accuracy data from 48 normal hearing listeners were obtained and published (1). Then identical measures were obtained from a wide variety of CI patients including patients with a CI for each ear (2, 6, 12, 14, 35, 36, 41, 44), a CI at one ear and a hearing aid at the other ear (2, 32, 34, 35, 37, 38, 39, 40, 41, 42, 44), and a CI at one ear and unaided normal (or near normal) hearing at the other ear (10). In each study the basic measure was a comparison of sound source localization accuracy performance for a normal hearing control group as compared to that for patients in the various CI groups. There were a wide variety of findings that are informative about both normal hearing sound source localization and that achievable by CI users. In all cases CI users' performance indicated poorer sound source localization accuracy than the normal controls, and in some cases CI patients were unable to localize sounds above a chance level of performance. When CI patients in the different groups could localize the source of sound, they did so mainly when sounds contained high-frequency information (sounds either had a bandwidth of 125-8000 Hz and/or 2000 to 8000 Hz). Most, but not all, CI patients performed very poorly, if at all, in the sound source localization task when the sound had a 125-500 Hz bandwidth. These results suggest that CI patients who are provided information to both ears can localize sound sources when the probable cue is the interaural level difference (ILD cues are used to localize high-frequency sounds). ILD cues are available via a CI to these patients, but due to the way in which the cochlear implant operates interaural time difference (ITD) cues, which provide location information at low frequencies, are not available. These results are helping inform CI development and use so that CIs may provide better spatial information in the future. And, the results clearly document that CI users who receive acoustic input to both ears

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can, in most cases, localize sound sources that they cannot do with a CI fit to only one ear.

Separate Sound Source Localization Accuracy

A series of studies using sound source localization identification was conducted both to collect baseline data for studies of multiple sound source localization and because there are few comprehensive studies of sound source localization identification in a near open field in the front azimuth plane (conditions in which sound source localization is primarily, if not entirely, based on binaural processing).

The first study (5) used normal hearing 48 subjects in a sound source localization identification task. The stimuli were filtered 200-ms, noise bursts: 125-500 Hz (LF: Low Frequency condition), 2000-8000 Hz (HF: High Frequency condition), and 125-8000 Hz (BB: Broad Band condition). Sound source localization is most likely based on interaural time difference (ITD) processing in the LF condition, most likely due to interaural level differences (ILD) in the HF condition, and most likely due to both ITD and ILD processing in the BB condition. The results from the “large n (48 subjects)” study indicated that sound source localization accuracy in the identification task when expressed as mean root-mean-square (rms) error was 6.2^{o} independent of the type of filtering used. That is, for these two or more octave wide noise stimuli sound source localization accuracy is not different when ITD processing, or ILD processing, or both ITD and ILD processing are used.

In a large scale follow-up study (8) sound source localization accuracy was measured as a function of the bandwidth and center frequency (CF) of the bandpass filters used to process the 200-ms noise bursts. Bandwidths from 1/20 of an octave to two octaves (along with tonal stimuli) were used and the CFs of the filters (or the tonal frequencies) were either 250 Hz (the spectral region where ITD processing most likely occurs), 4000 Hz (the spectral region where ILD processing most likely occurs), and 2000 Hz (the spectral region where neither ITD nor ILD cues provide good information about spatial location of sound sources). A broadband noise (125-8000 Hz) was also used in which it is assumed that listeners can use both ITD and ILD cues for sound source localization.

The results showed that when the band width of the noise was broader than one octave, sound source localization accuracy as measured by rms error in degrees did not vary as a function of CF; and rms error was smallest for these broadband noise stimuli (i.e., sound source localization accuracy was best and the rms error did not decrease for bandwidths greater than one octave). As the bandwidth of the noise decreased from one octave to $1/20^{th}$ of an octave rms error increased, and the amount of the increase was CF dependent such that best performance always occurred for the CF=250-Hz condition, worse performance for the CF=2000-Hz condition, and immediate accuracy performance for the CF=4000-Hz condition.

This study was conducted for a 200-ms noise burst presented at 65 dBA. The literature on spatial hearing using headphone delivered stimuli show that sound duration effects

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interaural time discrimination thresholds. By implication that would suggest that duration would affect sound source localization accuracy in an open field. There a few data in the literature related to sound source localization accuracy and duration when sounds are presented in an open field. Since there are also not clear data in the literature on the effect of over all level on sound source localization accuracy, we (14) decided to measure sound source localization accuracy as a function of noise duration and overall level. We did so for two-octave and 1/10th octave wide noises at CFs of 250 Hz and 4000 Hz.

The results (14) were that sound source localization accuracy was poorer for the 1/10th octave than for the two-octave wide noise, as we shown previously (8). Accuracy did not change for the two-octave wide noise for the two CFs, but for the 1/10th octave wide noise, accuracy was lower for 4000-Hz CF. All of these results are the same as for the bandwidth/CF sound source localization accuracy study described above. In NONE of the conditions did accuracy vary as a function of overall sound level (over the range of 25 to 85 dB dBA) and duration (over the range of 25 ms to 450 ms). Thus, in the open field, unlike under headphone conditions, sound source localization processing does not appear to depend on overall sound level or duration. We are not sure why the open field results differ from the results obtained over headphones when duration is varied, but at least one other study (46) also showed that sound source localization accuracy in an open field does not depend on noise duration.

It is also the case that for headphone delivered stimuli, ITD discrimination thresholds and the position of lateralized images vary as a function of the envelope of the sound in high-frequency regions where ITD processing would not occur due to the temporal fine structure of the stimuli. These lateralization results strongly suggest that ITD processing can occur based on the envelope of the sound, as along as the envelope fluctuations are slower than approximately 300 Hz. It is also the case that ITD processing based on envelope ITDs is worse than that based on temporal fine structure cues. Almost no studies have investigated envelope ITD processing in the open field, and the few studies that have (4, 47) have not found evidence for envelope ITD processing. Thus, we conducted a study (44) investigating the effect of envelope on sound source localization accuracy in the open field.

The study used sinusoidal amplitude modulation (SAM) and transposed stimulus amplitude modulation (TSAM) of filtered noise stimuli and a 4000-Hz tone (a stimulus often used in headphone lateralization studies). The study also investigated filtered and unfiltered click trains, when the click rate and number of clicks were varied (stimulus parameters that affect headphone measurements of ITD processing). Introducing an envelope did not change the sound source localization accuracy of any of the noise stimuli independent of the type of envelope modulation. A TSAM 4000-Hz tone had a slightly lower rms error (1^{o}) as compared to the rms error for an un-modulated 4000-Hz tone. Sound source localization accuracy for click stimuli is slightly lower (1-2^{o} rms error) than for short duration (25 ms) noise stimuli, but rms error does not change as a function of adding more clicks or as a function of the rate at which the multiple clicks are presented. Thus, unlike changes that occur over headphones in lateralization tasks providing an envelope does not change, or barely changes, sound source localization

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accuracy. A major reason is that in the open field ILD cues are always available, whereas in the headphone studies ILD differences are always set to zero not allowing for ILD changes to be used as a basis of lateralization performance. Even when sound source localization accuracy is poor in the open field (i.e., for narrow band noise stimuli with high-frequency CFs or for a 4000-Hz tone), providing an envelope to the narrow band stimuli usually does not improve sound source localization accuracy, and if it does the improvement is very small. It is also the case that sound source localization accuracy is measured in the open field and ITD discrimination is often measured over headphones.

Thus, this series of single sound source localization studies suggests that the main variable that influences sound source localization accuracy is stimulus bandwidth. The results also show that for narrow bandwidth stimuli (<1 octave wide) best accuracy occurs for low-frequency sounds (<500 Hz), worse performance for mid-frequency sounds (around 2000 Hz), and intermediate accuracy for high-frequency sounds (>4000 Hz). The duration and overall level of sound, as well as a sound's envelope appear to have very little effect on sound source localization accuracy (at least in the front azimuth hemifield). These results do not always occur when interaural discrimination or lateralization are measured over headphones. Additional studies are being planned to investigate the reasons for the differences between open field and lateralization measures.

Multiple Sound Source Localization

A large scale study was completed (4) in which subjects were asked to determine the location of two simultaneously presented sound sources each producing a 200-ms, wideband, and independently generated, noise burst. The main finding of the study was that listeners can localize the position of each of the two sources (in the front azimuth field), but not as well as they can localize the position of a single noise burst. Since two independently generated wideband noise bursts are as similar as two sounds can be in terms of sound source localization, the data suggest that the location of almost any two sounds presented at the same time could probably be determined (i.e., all other types of sounds would have greater acoustic differences which could be used as a basis for sound source localization).

The paper suggested a process by which the auditory system might determine the location of two (or maybe more) simultaneously presented sounds. The process consists of dividing the combined sound waveform from two (or more) sources into a matrix of small time/frequency cells. Then the ITDs and ILDs of the waveform in each cell are computed. If a sufficient number of the cells in the combined waveform matrix have ITD and ILD values consistent with those of one or the other of the two (or more) sound sources when they are presented alone, then there might be sufficient information in this matrix to identify the two locations. An amplitude modulation noise task was used to test the idea of this approach. The results suggested that such a process might be used to determine the location of at least two sound sources, and the experiment and its analysis suggested that the temporal width of the cells in such a matrix might be on the order of 5 ms and the spectral height about one critical bandwidth.

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This experiment described above tested one vs. two spatially separated sound sources. Another experiment (16) was conducted in order to obtain information about how many simultaneous spatially separated sound sources might be localizable. Both the accuracy of determining how many sources were presenting sound (numerosity) and listeners' ability to determine the location of these sources were measured. The sounds were either one-word country names or tones of different frequencies. The results strongly imply that no more than four simultaneous spatially-separated word sources and no more than two-three simultaneously presented spatially-separated tonal sources can be determined, even when as many as eight sources produce sound. Two other very recent studies (48, 49) have produced similar results.

In the studies described above and in most of the literature on multiple sound source localization the sound sources were stationary. A study (31) was conducted to determine if moving sound sources might allow for better segregation of sound sources, as relative motion of visual object is a powerful cue for separating foreground objects from background objects. Speech sounds (words) and tones whose frequencies were either harmonics of 250 Hz, harmonics of 250 Hz except for the second harmonic whose frequency was "mistuned" to 613 Hz (from the harmonic of 500 Hz, e.g., rather than tones of 250, 500, 750 and 1000 Hz for the harmonic case, the tones were 250, 613, 750, and 1000 Hz for this "miss-tuned harmonic case"), and tones of random frequency each within an octave of the relative harmonics of 250 Hz. Sounds were presented simultaneously at different spatial source locations (either three, four, or six locations), with the spatial locations maximally different (e.g., for four tones, at 0^o, 90^o, 180^o, and 270^o). Either all sounds (three, four, or six) rotated around the azimuth circle at the same time or one sound rotated while the other sounds remained at fixed locations. When either all words or one word rotated listeners could determine the direction of rotation. But listeners could do so when all words rotated by attending to only one word at a time, i.e., attending to the "chorus" of all of the words (three, four, or six) did not produce any motion perception. Listeners could not determine (i.e., performance was at chance) the direction of rotation for harmonically related tones, and performance was marginally better than chance (approximately 70-75% correct in determining the direction of rotation) for the miss-tuned harmonic condition and the random frequency condition. These results suggest that perceiving sound source motion of multiple sounds is very dependent on the perceptual relationship of one sound to the other sounds (e.g., are sounds harmonically related?). The results also suggest that sound source motion may not be a good cue for segregating sound sources.

In the paper (31) in which listeners were asked to determine the number of sound sources they perceived, making the sound at one source more intense would most likely increase its probability of being perceived. This is similar to a spatial release from masking (SRM) study in which the threshold for detecting, discriminating, or recognizing a target sound in the presence of spatially separated masker sound sources is lower (target easier to process) than if the target and maskers are all co-located at the same source. In most SRM studies the maskers are asymmetrically located relative to a centered target sound source. In these cases the target may be processed based on binaural processing and/or because the target-to-masker ratio is higher at the ear furthest from the masker sound

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source (i.e., the masker is masked by the head, i.e., head shadow). When the masker sources are symmetrically spaced around a target source, target processing would have to be based on binaural processing as both ears receive the same target-to-masker ratio.

A large-scale study (18) was conducted to determine SRM for masker source configurations in which the maskers were always symmetrically located relative to a centered target sound source (i.e., when target processing in the presence of the masker would involve only binaural processing). Two, four, or six maskers (all one-word country names uttered by male talkers) were used to mask centered target words (one-word country names uttered by a female talker). Masking when the maskers were spatially separated from the target was compared to conditions when all words (target and maskers) were co-located at the center loudspeaker (always the location of the target word). Masking was also measured when the maskers were filtered and modulated noise bursts and when the target and masker words were filtered through different filters. When maskers are noises, masking is assumed to be primarily “energetic” masking. When the maskers and target words are differentially filter to reduce spectral overlap of the masker and target sounds, masking is primarily “informational” (i.e., masking is largely due to the similarity of the masker and target words). When the target and masker sounds are both unfiltered words, masking is assumed to be a combination of “energetic” and “informational” masking. Thus, in addition to varying the number of maskers the type of masker was also varied: unfiltered speech, filter and modulated noise, or filtered speech. The target was always speech, but when the masker was filtered speech the target was also filtered but using different filters than those used to filter the target word.

In this study, SRM (difference in word recognition between the co-located and spatially separated masker conditions) decreased as the number of maskers increased from two to six, and there was almost no SRM for the six-masker conditions. The decrease in SRM occurred for the noise maskers (energetic masking), for the differentially filtered maskers (informational masking), and for the unfiltered speech maskers (combination of energetic and informational masking). In fact masking of speech targets by speech maskers (a combination of energetic and informational masking) was equal to the sum of noise masking (energetic masking) and the differentially filtered targets and maskers (informational masking) for all conditions.

These data reinforce the previous work suggesting that the auditory system cannot differentially process more than about four simultaneous speech sounds even when their sources are spatially separated. In the SRM study making one of the sounds (the target sound) more intense did not improve its intelligibility when more than four masking sounds were spatially separated from the target sound sources as compared to when all sounds were co-located at the same loudspeaker.

Thus several studies lead to the conclusion that the auditory scene is small, probably limited to four or fewer sound sources, when the sound from all of the sources occur at about the same time. It is probable that human listening cannot segregate more than about four sound sources without the aid of some external signal-processing device.

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In 1939 Wallach proposed that not only could head movements help resolve cone-of-confusion errors, but head movements could also facilitate sound source localization off the azimuth plane in elevation. We (17) conducted experiments based on signal processing algorithms to determine if an automated systems could be developed to use head movements to determine multiple sound sources in both azimuth and elevation. Both a cross-correlation approach and a Kalman filter application indicated that head motion could be used to determine three sound sources that were located at different elevations and azimuths. Thus, systems that involve receiver motion might be advantageous in sound source localization tasks

Sound Source Localization When Listeners Move

At the beginning of the grant period the Spatial Hearing Lab was renovated to add additional loudspeakers and to include a computer controlled rotating chair. As a result a series of studies was undertaken to study sound source localization processing when a listener moves (i.e. a listener is rotated in the computer controlled chair). A large scale study (11) and several pilot studies (16, 19, 22, 28, 29, 30, 31, 44) have been conducted related to this topic.

The basic hypothesis is that sound source localization requires two forms of information: 1) Information about the auditory spatial cues, and 2) Information about the location of the head. That is, when the head moves the auditory spatial cues change and information about the position of the head is required so that a stabilized (veridical) perception of auditory space can occur. To test this hypotheses (see 11) listeners were rotated in the chair and were asked to make sound source rotation and location decisions. They did so with their eyes open or closed to control visual input and under constant velocity or acceleration/deceleration rotation conditions to control for vestibular input. Since the listeners are rotated (as opposed to moving themselves) at a slow velocity, there are no proprioceptive, kinesthetic, or somatosensory cues related to rotation. And, no prior experience or feedback was provided to the listener about their rotation, so there was no cognitive information based on experience that was related to their rotation.

In several experiments (11, 19, 20, 22, 23, 28, 29, 31, 32, 45) the following results were obtained when the listeners rotated at constant velocity with their eyes closed; thus depriving them of all information about the position of their head. The prediction is that in this case sound source location and rotation information would be based on only auditory spatial cues leading to all spatial perceptions being based on a head-centric reference system (as opposed to the normal world-centric reference system used to maintain a veridical perception of auditory space):

A) Stationary sound sources were perceived as rotating in a direction opposite of the listener's rotation.
B) When the sound source and the listener rotated at the same velocity, listeners did not perceive the sound rotating.
C) When the sound source rotated slower than the listener rotated, listener's perceived the direction of sound rotation as opposite that of the actual sound

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rotation, while when the sound rotated at a velocity faster than the listener, the perception of the direction of sound rotation was the same as the actual rotation.

D) Listeners were at chance in their ability to locate the source of the sound in a world-centric reference system (i.e., at chance in indicating which loudspeaker presented a sound), but could with a little practice indicate where they perceived the source relative to their head (i.e., in a head-centric reference system).

All of these outcomes are consistent with listeners only being able to judge the head-centric location of sound since they were deprived of any information about the position of their head. Thus, the data support the hypothesis that in the everyday world two pieces of information (spatial cues and head position cues) are required to locate the actual position of sound sources (e.g., to operate in a world-centric reference system).

Experiments are underway investigating how listener and sound motion affects cones-of-confusion errors (e.g., front-back errors when the same ITDs and ILDs can be generated by more than one sound source location, see 30). Experiments are also exploring the extent to which multiple sound sources and somatosensory cues can help listeners determine head position and, thus, allow them to localize the actual position of sound sources (i.e., in a world-centric reference system) when they are deprived of visual and vestibular information.

Published Papers, Papers in Press, Invited Presentations, and Contributed Presentations supported by the AFOSR grant. Reference to key citations are provided above.

<u>Published Papers:</u>

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<ins>In Press:</ins>

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17) Zhong, X., Sun, L., and William Yost. Active Binaural Localization of Multiple Sound Sources, Robotics and Autonomous Systems, in press
18) Yost, William A. Spatial release from masking as function of the number of maskers, Journal of the Acoustical Society of America, submitted

<ins>Invited Presentations:</ins>

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19) Yost, William A. and Xuan Zhong: Sound Source Localization: Where am I, Where is the Source? Acoustical Society of America, San Francisco (Session honoring Erv Hafter), 2013
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FA9950-12-1-0312

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Willaim A Yost

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Abstract

The AFOSR Grant, FA9550-12-1-0312, has supported the Spatial Hearing Laboratory (SHL) at Arizona State University for the past four years. The research conducted in the SHL has involved four main topics: Sound Source Localization by Cochlear Implant (CI) Patients, Single Sound Source Localization Accuracy, Multiple Sound Source Localization Identification, and Sound Source Localization When Listeners Move. The CI research was also supported by an NIH grant ("Cochlear Implant Performance in Realistic Listening Environments," Dr. Michael Dorman, Principal Investigator, Dr. William Yost unpaid advisor. The other three topics cited above are entirely within the scope of the AFOSR grant.

Sound Source Localization by Cochlear Implant (CI) Patients: Several studies were conducted with three patient populations (bilateral CI patents, CI patients with a CI at one ear and a hearing aid fit to other ear, and CT patients with one CI and normal or unaided near normal hearing at the other ear) showing that CI patients who receive bilateral input can in most cases localize the source of sound but not as well as normal hearing individuals. When CI patients can localize sound sources they usually do so by using interaural level differences (ILDs) and not interaural time differences (ITDs).

Single Sound Source Localization Accuracy: Several experiments were conducted using a sound source localization identification task to determine the variable that determine sound source localization accuracy for a single sound source in the front azimuth plane. Stimulus bandwidth is the most important variable with stimuli having bandwidths greater than one octave yielding the best accuracy, and accuracy depends on the frequency region of stimulation for bandwidths less than an octave. Stimulus duration, overall level, and amplitude envelope have a very small, if any, effect on sound source localization accuracy.

Multiple Sound Source Localization Identification: Two independent noise sources can be located in the frontal azimuth plane but not as well as one noise source. A scheme in which the combined two-noise stimulus is analyzed for interaural time and level differences in small temporal/spectral cells calculated for the combined stimulus was shown to be a possible way in which two or more simultaneous sounds could be localized at different sources. Several studies indicate that the maximum number of spatially separated and simultaneously presented sound sources that can be identified and localized is about four for speech sounds and two-three for tonal sounds. Moving one or more sound source only assists in segregating one sound source from other sound sources when the sounds are not perceptually similar.

Sound Source Localization When Listeners Move: The results from several experiments support the hypothesis that sound source localization must be based on two pieces of information: information about the auditory spatial cues and information about the position of the listener's head. By moving (rotating) listeners while they perform sound source localization tasks, it was revealed that listeners require information about the position of their heads in order to successfully determine the veridical location of sources in the actual world.

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2. New discoveries, inventions, or patent disclosures:
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Research Objectives

Technical Summary

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